Turbulent Air-Sea Exchange in Extreme Winds and Its Effects on Storm Structure

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Contract Number: N000140810411
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LONG-TERM GOALS

The goal is to investigate, theoretically and through analyzing existing data, sea surface physics and air-sea exchange in extreme winds. This is a collaboration between Ed Andreas and Kerry Emanuel. Our underlying motivations are improving predictions of tropical cyclone intensity and structure and developing guidelines for planning an eventual field experiment to observe the air-sea drag and enthalpy exchange in high winds. . Ultimately these goals require our developing physics-based parameterizations and theoretical constraints for turbulent air-sea fluxes in extreme winds. One focus will be on the role that sea spray plays in transferring heat, moisture, and momentum across the air-sea interface in high winds.

OBJECTIVES

1. Continue analyzing data sets collected in high winds (e.g., HEXOS, FASTEX, CBLAST, Duck) to deduce surface fluxes and develop parameterizations for the air-sea fluxes of enthalpy and momentum that begin to probe the behavior of the sea surface in hurricane-strength winds.

2. Undertake theoretical work to identify processes near the air-sea interface in extreme winds that affect the air-sea exchange of enthalpy and momentum. Develop physical constraints for these processes and tentative parameterizations for them.

3. Do sensitivity studies using various ocean storm models to evaluate how the parameterizations for air-sea coupling that we develop affect predictions of tropical cyclone intensity and structure as well as the responses of the ocean and atmosphere to strong forcing.

4. Using theory and models, combined with inferences about surface fluxes from the first three objectives, quantify the sensitivity of a storm’s inner and outer structure and the evolution of that structure to assumptions about surface fluxes and other environmental factors.

APPROACH

This work is theoretical and analytical; it has no experimental component. Andreas is the only NWRA participant but will be collaborating with Kerry Emanuel of MIT.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
30 SEP 2008	**Annual**	**00-00-2008 to 00-00-2008**

4. TITLE AND SUBTITLE
Turbulent Air-Sea Exchange In Extreme Winds And Its Effects On Storm Structure

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
NorthWest Research Associates, Inc. (Seattle Division),25 Eagle Ridge,Lebanon,NH,03766-1900

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
Code 1 only

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Same as Report (SAR)**	**10**	

A main emphasis of this work is on how sea spray mediates the air-sea fluxes. Microphysical theory establishes how rapidly spray droplets can exchange heat and moisture in a given environment. Theory also predicts how sea spray production should depend on wind speed and how spray droplets should be distributed in the near-surface air. The analytical part involves developing parameterizations for the various spray transfer processes by simplifying model results or by synthesizing various data sets and observations. Checking the parameterizations against available data is also another aspect of what I call analytical work.

As just one example of this recent theoretical and analytical work, I have developed a parameterization for the salt flux to the ocean surface that is mediated by sea spray. To my knowledge, no one has recognized before that spray can affect the ocean's buoyancy by adding salt to the surface. This conclusion, however, is a necessary extension of Andreas and Emanuel's (2001) concept of re-entrant spray. They recognized that only spray droplets that are flung into the air, cool, and then fall back into the sea can affect the net enthalpy flux across the air-sea interface. But similarly, droplets that are flung into the air, evaporate some of their water, and fall back into the sea are saltier than the surface water from which they formed. Their evaporation and re-entry into the ocean constitutes a surface source of salt.

In my recently published bulk flux algorithm for high-wind, spray conditions (Andreas et al. 2008), we modeled the total air-sea fluxes of latent ($H_{L,T}$) and sensible ($H_{s,T}$) heat as follows:

$$H_{L,T} = H_L + \alpha \overline{Q}_L \ , \tag{1a}$$

$$H_{s,T} = H_s + \beta \overline{Q}_S - (\alpha - \gamma) \overline{Q}_L \ . \tag{1b}$$

Here, H_L and H_s are the interfacial latent and sensible heat fluxes, which we model with the COARE Version 2.6 bulk interfacial flux algorithm (Fairall et al. 1996). The $\overline{Q}_L$ and $\overline{Q}_S$ are "nominal" spray fluxes that we compute with my full microphysical spray model (Andreas 1989) and knowledge of the spray generation function (Andreas 2002) by integrating over all droplet sizes relevant to the spray heat transfer. That is, $\overline{Q}_L$ and $\overline{Q}_S$ include a lot of microphysical calculation that are theoretically based but occur "off stage" in the context of (1).

Finally, the α, β, and γ are small, non-negative coefficients that we use to tune (1) to data. Andreas et al. (2008) used data from HEXOS, the study of Humidity Exchange over the Sea, and FASTEX, the Fronts and Atlantic Storm-Tracks Experiment—two very good high-wind experiments—to obtain $\alpha = 1.5$, $\beta = 10.5$, and $\gamma = 0.2$. In a modeling sense, the total fluxes represented as the left sides of (1) would serve as the lower flux boundary condition for an atmospheric model.

The latent heat flux at the air-sea interface results from evaporation and, therefore, produces a salt flux to the ocean. If the fractional surface salinity is s, the interfacial latent heat flux H_L is associated with an interfacial salt flux of

$$F_{salt,int} = \frac{s H_L}{L_v (1 - s)} \ , \tag{2}$$

where L_v is the latent heat of vaporization of water.

Andreas et al. (2008; also Andreas and DeCosmo 1999, 2002) compute $\overline{Q}_L$ in (1a) from

$$\overline{Q}_L = \int_{r_{lo}}^{r_{hi}} Q_L(r_0)\, dr_0 \quad , \tag{3}$$

where $Q_L(r_0)$ is the spray latent heat flux contributed by all droplets of initial radius r_0, and r_{lo} ($=1.6\,\mu m$) and r_{hi} ($=500\,\mu m$) are the smallest and largest droplets that contribute appreciably to this integral. Only the droplets that fall back into the sea, however, contribute to the spray salt flux. These are the larger droplets; suppose they have radii of at least r_{cut}, a cut-off radius that depends on environmental conditions such as wind speed and ambient temperature and relative humidity. Thus, using the same α that we obtained for (1a)—because I have no other means to evaluate α—my estimate of the spray salt flux is

$$F_{salt,sp} = \frac{\alpha s}{L_v(1-s)} \int_{r_{cut}}^{r_{hi}} Q_L(r_0)\, dr_0 \quad . \tag{4}$$

Figure 1 shows my calculations of the total salt flux, $F_{salt,T}$ from (2), where here H_L is the total measured latent heat flux ($H_{L,T}$) from the HEXOS and FASTEX data. The figure also shows the spray salt flux, $F_{salt,sp}$ from (4). The measured salt flux starts larger than the spray salt flux but, because at low wind speed it depends approximately linearly on wind speed, does not increase very rapidly. Although the spray salt flux starts out low, because it increases faster than the square of the wind speed, it will eventually equal and dominate the total salt flux in storm winds. This spray salt flux will clearly increase buoyancy mixing in the ocean in high winds and could be an important air-sea coupling mechanism in storms.

This has been just one example of my approach in this project: to use theory, data analysis, and interpretation to better understand sea surface physics in very high winds.

WORK COMPLETED

The highlight of this year was the publication of my flux algorithm for high-wind, spray conditions, Andreas et al. (2008), which, as I described, is based on analyses of HEXOS and FASTEX data and builds on Andreas and DeCosmo's (1999, 2002) analyses of just the HEXOS data.

Andreas et al. (2006) recently reported their analysis of the largest data set ever used to evaluate the von Kármán constant, k, in the atmospheric surface layer—553 measurements. We concluded that k is a bit lower than the canonical value of 0.40; our value is 0.387 ± 0.003.

Because k appears prominently in all bulk flux algorithms, I want to update my flux algorithm to reflect this new value. But any such changes must be made carefully because k occurs everywhere in the mathematics of the atmospheric boundary layer; many empirical coefficients and functions therefore depend on the value of k assumed in the original data analysis. Before I update my flux

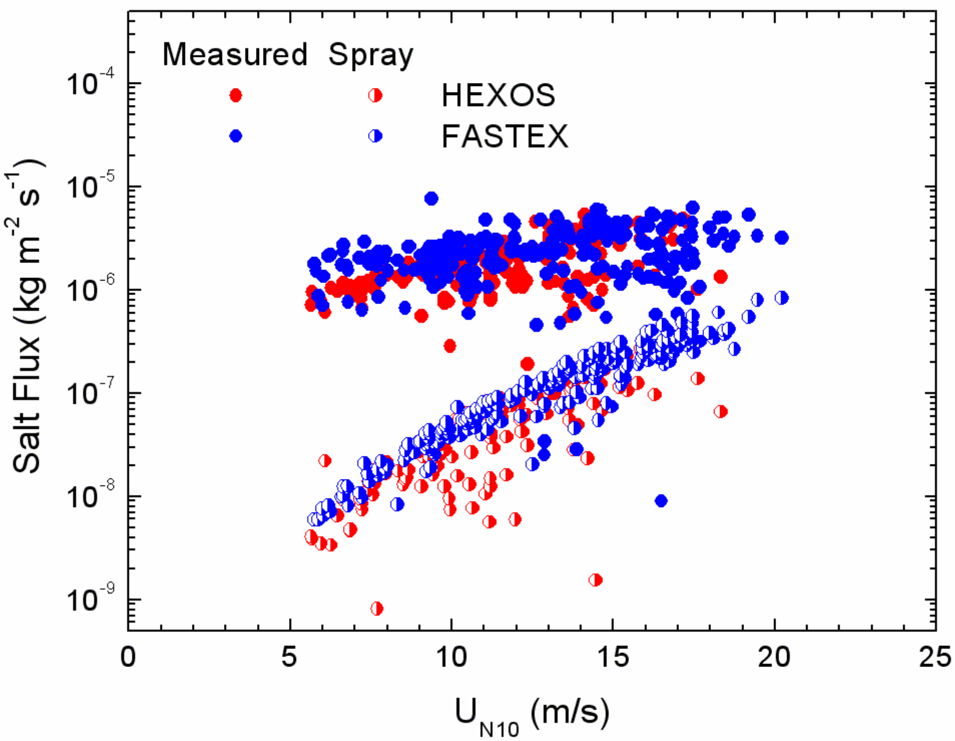

Fig. 1. Calculations of the total salt flux, $F_{salt,T}$, using (2) and measurements of the total latent heat flux ($H_{L,T}$) during HEXOS and FASTEX, and corresponding estimates of the spray salt flux from (4). The measured salt flux is around 10^{-6} kg m^{-2} s^{-1} and increases slowly with the neutral-stability, 10-m wind speed, U_{N10}. The spray salt flux starts at about 10^{-8} kg m^{-2} s^{-1} for U_{N10} = 5 m s^{-1} but increase to 10^{-6} kg m^{-2} s^{-1} for U_{N10} = 20 m s^{-1} because it increases faster than the square of the wind speed.

algorithm, I wrote a manuscript that develops a rational way to implement a new value of the von Kármán constant in many of the equations used to describe the atmospheric boundary layer (Andreas 2008). That manuscript is in the final stages of review.

Finally, I have been collaborating with Gerrit de Leeuw, Chris Fairall, and several others to prepare a manuscript that reviews our current understanding of sea spray generation and dispersion (de Leeuw et al. 2008). The spray generation function, usually denoted dF/dr_0—the number of droplets produced per square meter of sea surface area, per second, per micrometer increment in the droplet radius at formation, r_0—is crucial to all my work (Andreas 2002). For example, it is one of the variables hidden in $\overline{Q}_L$ and $\overline{Q}_S$ in (1) and in $Q_L(r_0)$ in (3) and (4).

Figure 2 shows a summary figure that I have contributed to this manuscript. It depicts the spray volume flux, $\left(4\pi r_0^3/3\right) dF/dr_0$, for a 10-m wind speed of 20 m s^{-1} for the functions that Andreas (2002) concluded were most reliable and for several new estimates of the spray generation function. Clearly, we still have some work to do to understand spray generation to better than half an order of magnitude.

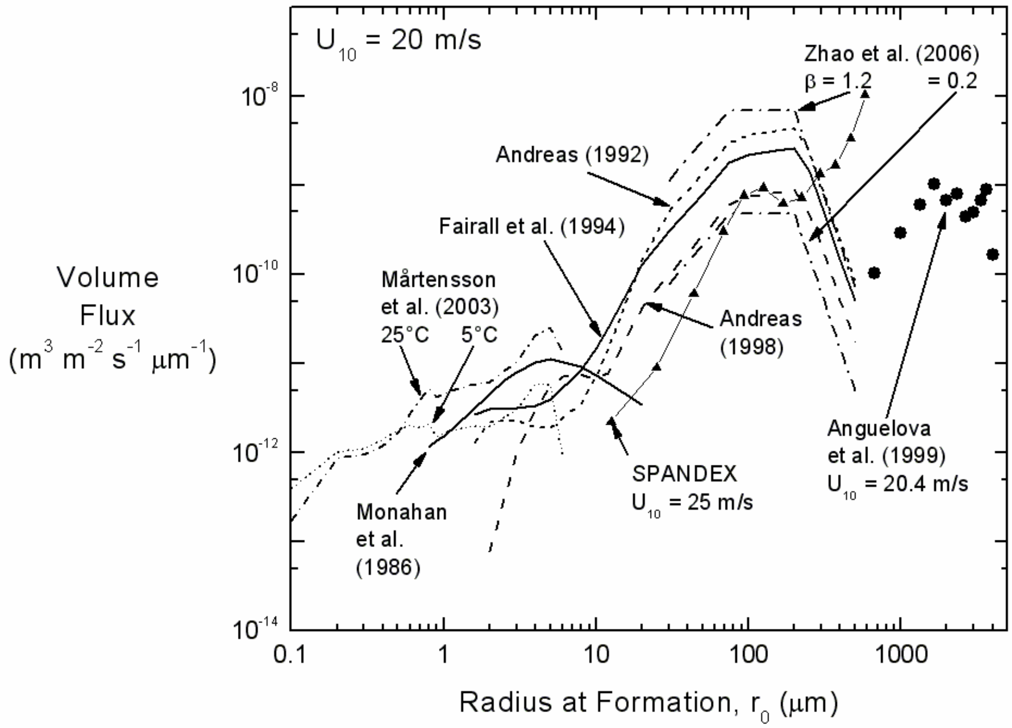

Fig. 2. Various estimates of the spray generation function expressed as a volume flux [i.e., $\left(4\pi r_0^3/3\right)dF/dr_0$] in terms of the droplet radius at formation, r_0, for a 10-m wind speed (U_{10}) of 20 m s^{-1}. Andreas's (2002) recommended functions were from Monahan et al. (1986), Andreas (1992), Fairall et al. (1994), and Andreas (1998). To these, I have added functions from Mårtensson et al. (2003), for water temperatures of 5° and 25°C; and from Zhao et al. (2006), for wave ages (β) of 0.2 and 1.2. The data from Anguelova et al. (1999) come from a wind-wave tunnel in which the equivalent 10-m wind speed was estimated to be 20.4 m s^{-1} and predict higher fluxes than all other expressions. Finally, the SPANDEX data (C. W. Fairall, 2008, personal communication) come from another study in a wind-wave tunnel with an equivalent 10-m wind speed of 25 m s^{-1}. Most of the functions agree that the spray volume flux is between 10^{-12} and $10^{-11}\ m^3\ m^{-2}\ s^{-1}\ \mu m$ for radii of 10 μm and smaller; most of the functions also agree that the volume flux has a pronounced peak between 10^{-9} and $10^{-8}\ m^3\ m^{-2}\ s^{-1}\ \mu m$ for droplets with radii around 100 μm.

RESULTS

To develop a fast parameterization for our bulk flux algorithm, Andreas et al. (2008) assumed that spray droplets with initial radius near 50 μm were good indicators of the total spray latent heat flux, $\alpha\overline{Q}_L$. They therefore parameterized this spray latent heat flux as

$$\alpha\overline{Q}_L = \rho_w L_v \left\{1 - \left[\frac{r\left(\tau_{f,50}\right)}{50\,\mu m}\right]^3\right\} V_L\left(u_*\right) . \tag{5}$$

Here, ρ_w is the density of seawater; V_L is a wind function that depends on the friction velocity, u_*; and r is the droplet radius as a function of time, t, where

$$r(t) = r_{eq} + \left(r_0 - r_{eq}\right)\exp\left(-t/\tau_r\right) . \tag{6}$$

In this, r_{eq} is the droplet radius at equilibrium, a function of temperature, relative humidity, salinity, and initial droplet radius, r_0. Also in (6), τ_r is the e-folding time for a droplet of initial radius r_0 to reach equilibrium. Finally, in (5), $\tau_{f,50}$ is the atmospheric residence time for droplets that started with radius of 50 μm. We base calculation of r_{eq} and τ_r on Andreas's (2005) fast microphysical algorithms.

Andreas et al. (2008) evaluated $V_L(u_*)$ from their partitioning of the HEXOS and FASTEX data into interfacial and spray contribution through (1). They obtained

$$V_L\left(u_*\right) = 1.10\times10^{-7}\, u_*^{2.22} , \tag{7}$$

which gives V_L in m s^{-1} for u_* in m s^{-1}.

Because of the similarity between (3) and (4), I can presume that the spray salt flux follows scaling as in (5). That is, I hypothesize that, for a fast flux calculation, droplets of r_0 = 50 μm also are bellwethers of the spray salt flux and write

$$F_{salt,sp} = \rho_w\left(\frac{s}{1-s}\right)\left\{1-\left[\frac{r\left(\tau_{f,50}\right)}{50\,\mu m}\right]^3\right\}V_{salt}\left(u_*\right) . \tag{8}$$

Thus,

$$V_{salt}\left(u_*\right) = \frac{F_{salt,sp}}{\rho_w\left(\frac{s}{1-s}\right)\left\{1-\left[\frac{r\left(\tau_{f,50}\right)}{50\,\mu m}\right]^3\right\}} , \tag{9}$$

where $F_{salt,sp}$ is the spray salt flux shown in Fig. 1.

Figure 3 shows $V_{salt}(u_*)$ computed from (9) for the HEXOS and FASTEX data. The best-fitting line through the data is

$$V_{salt}\left(u_*\right) = 8.01\times10^{-8}\, u_*^{2.11} , \tag{10}$$

which gives V_{salt} in m s^{-1} for u_* in m s^{-1}. Notice, (10) has almost the same u_* dependence as V_L in (7) but is slightly below that line. I conclude that the droplets left out of the $F_{salt,sp}$ computation, those for which $r_{lo} \le r_0 \le r_{cut}$, do not contribute very much to the spray latent heat flux, $\alpha\overline{Q}_L$.

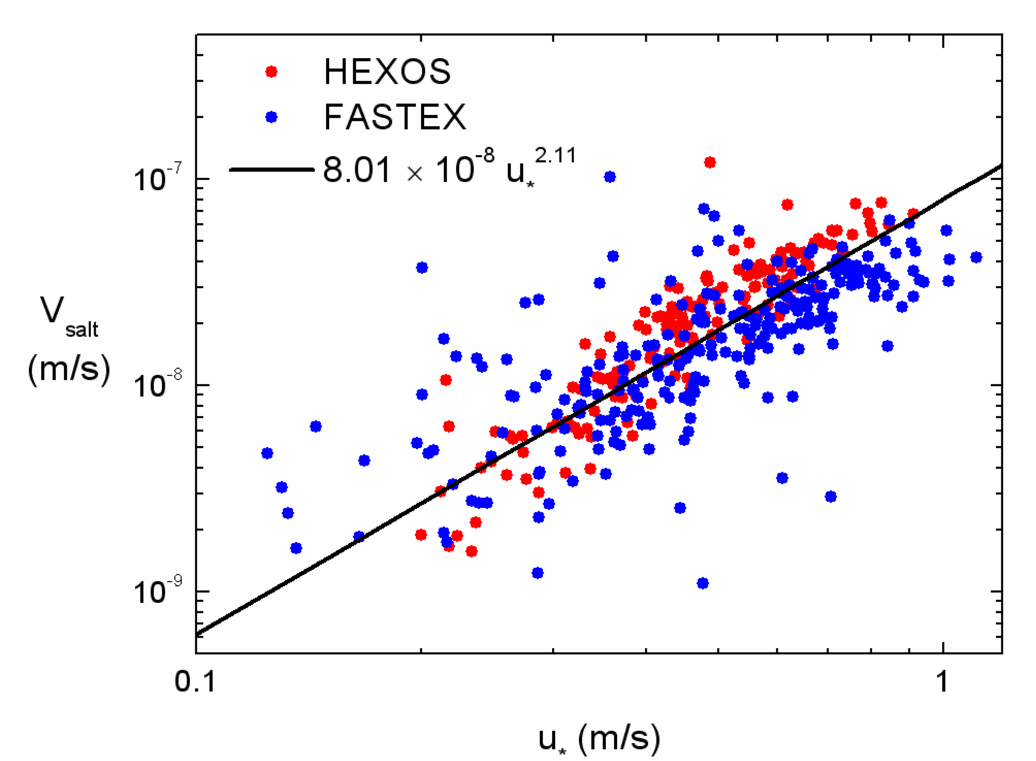

Fig. 3. The spray salt flux, $F_{salt,sp}$, that was obtained from the HEXOS and FASTEX data and shown in Fig. 1 is parameterized here as in (8). That is, this plot shows the derivation of the wind function $V_{salt}(u_*) = 8.01\times 10^{-8} u_*^{2.11}$, which is the straight line fitted through the data on this log-log plot.

I will incorporate (8) and (10) into the next version of my bulk flux algorithm.

IMPACT/APPLICATIONS

The turbulent air-sea flux algorithm that I have developed has three features that are not all present in any other air-sea flux algorithm: It explicitly recognizes two routes by which heat and momentum cross the air-sea interface, the usual interfacial route and the spray-mediated route; it has been verified against data; and it is theoretically based and, therefore, can be extrapolated to high-wind conditions. My recognizing that evaporating spray can also add salt flux to the ocean surface and my developing a parameterization for this flux is now a fourth feature that no other air-sea flux coupler has.

Although I have tested this algorithm against in situ data, we still need to see if it improves predictions of ocean storm structure and intensity. I am currently working with Kerry Emanuel to address this issue. But I have also had a long collaboration with Will Perrie and his colleagues at Bedford Institute of Oceanography. In fact, they have done the most work in testing my algorithm in ocean storm simulations and have documented their finding in Perrie et al. (2004, 2005, 2006), Zhang et al. (2006), and Zhang and Perrie (2008). Generally, they find that including the spray heat fluxes in their coupled mesoscale model gives better predictions for the intensity of extratropical storms when central pressure and maximum surface-level wind speed are used as metrics of storm intensity.

TRANSITIONS

Besides my journal articles and conference presentations that describe my work on air-sea exchange in high winds, I have developed a software "kit" that contains the instructions and FORTRAN programs necessary to implement my bulk flux algorithm. Version 3.1 is the current version of that code. Version 3.2, soon to be released, will include the new modules for computing the interfacial and spray salt fluxes. I distribute this kit to anyone who asks about using my algorithm.

Another vehicle for transitions is my membership on the American Meteorological Society's Committee on Air-Sea Interaction. For example, on behalf of our committee, during a special session on transitioning research to applications at the 2008 AMS Annual Meeting in January, I gave an invited talk on success stories and lessons learned in air-sea interaction research. Secondly, I am the co-chairperson of the program committee for the 16th Conference on Air-Sea Interaction, to be held in January 2009 during the Annual Meeting of the AMS in Phoenix. In that role, I arranged for several sessions relevant to the subject of my current research for ONR. Namely, that conference will have two session (with 12 talks) on Sea Surface Physics and two sessions (with 11 talks) on Tropical and Extratropical Storms.

Finally, I am a member of James Mueller's Ph.D. thesis advisory committee. James is Fabrice Veron's student in the College of Marine and Earth Studies at the University of Delaware and is working on a topic very close to my own research—spray generation and dispersion and the role that spray plays in air-sea heat and momentum exchange. I have been learning things from James's research; and, hopefully, he has found my advice useful.

RELATED PROJECTS

I am just finishing a one-year project funded by the Mineral Management Service. Kathleen F. Jones of the U.S. Army Cold Regions Research and Engineering Laboratory is the PI and has been funding me as a subcontractor. Our objective is to develop guidelines for predicting spray icing on permanent platforms (usually drilling platforms) in the waters around Alaska. Spray icing is a hazard to both personnel and equipment during high-wind events with sub-zero temperatures. That is, the conditions of interest in the spray icing project overlap some of the conditions that are important in this ONR project. The two projects, thus, mutually leverage each other. For the spray icing project, we have been developing equations for predicting the vertical profile in spray concentration as a function of droplet radius from what I know about the sea spray generation function.

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Andreas, E. L, 2008: A new value of the von Kármán constant: Implications and Implementation. *Journal of Applied Meteorology and Climatology*. [submitted, refereed]

Andreas, E. L, P. O. G. Persson, and J. E. Hare, 2008: A bulk turbulent air-sea flux algorithm for high-wind, spray conditions. *Journal of Physical Oceanography*, **38**, 1581–1596. [published, refereed]

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